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The Substellar Mass Function in σ Orionis

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ABSTRACT

We combine results from imaging searches for substellar objects in the σ Orionis cluster and follow-up photometric and spectroscopic observations to derive a census of the brown dwarf population in a region of 847 arcmin^2. We identify 64 very low-mass cluster member candidates in this region. We

have available three color (IZ and J) photometry for all of them, spectra for 9 objects, and K photometry for 27 % of our sample. These data provide a well defined sequence in the I versus $I-J$, $I-K$ color magnitude diagrams, and indicate that the cluster is affected by little reddening despite its young age (∼5 Myr). Using state-of-the-art evolutionary models, we derive a mass function from the low-mass stars ($0.2\,M_\odot$) across the complete brown dwarf domain ($0.075\,M_\odot$ to $0.013\,M_\odot$), and into the realm of free-floating planetary-mass objects ($\leq 0.013\,M_\odot$). We find that the mass spectrum $(dN/dm) \propto m^{-\alpha}$ increases toward lower masses with an exponent $\alpha = 0.8 \pm 0.4$. Our results suggest that planetary-mass isolated objects could be as common as brown dwarfs; both kinds of objects together would be as numerous as stars in the cluster. If the distribution of stellar and substellar masses in σ Orionis is representative of the Galactic disk, older and much lower luminosity free-floating planetary-mass objects with masses down to about 0.005 $M_\odot$ should be abundant in the solar vicinity, with a density similar to M-type stars.

Subject headings: open clusters and associations: individual (σ Orionis) — stars: low-mass, brown dwarfs — stars: mass function — stars: pre-main sequence

1. Introduction

Although there is no definitive theory to explain the formation processes of stars, the widely accepted scenario is that they form via fragmentation of rotating interstellar molecular clouds followed by gravitational collapse. However, given the typical conditions and properties of Galactic molecular clouds, this simple paradigm has difficulties (Bodenheimer 1998) in explaining the genesis of numerous populations of substellar objects ($M < 0.075\,M_\odot$). Several arguments have also been proposed against the formation of objects below the substellar boderline (Silk 1995) or below the deuterium-burning mass limit (Shu, Adams & Lizano 1987), which according to Saumon et al. (1996) and Burrows et al. (1997) is located in the range 0.013–0.011 $M_\odot$ (∼ 14–12 $M_{\rm Jup}$, where 1 $M_\odot$ = 1047 $M_{\rm Jup}$). The overall distribution of masses for invidual objects resulting from star-forming processes can be described by the mass function (MF), defined as the the number of objects per interval of mass on a logarithmic scale, $\xi(m) = dN/d\log m$, or alternatively by the mass spectrum defined as $\phi(m) = dN/dm$. The MF was first studied for the stellar regime by Salpeter (1955), who found that a power-law relation of the type $\xi(\mathrm{m}) \propto M^{-\gamma}$, with an index $\gamma = 1.35$, (which corresponds to $dN/dm \propto m^{-\alpha}$ with $\alpha = 2.35$ for the mass spectrum) was adequate in the mass range 1–10 $M_\odot$. Subsequent studies of the field MF appear to

demand lower values of α at smaller masses, or even suggest alternative functional forms (Miller & Scalo 1979). A recent study of the very low-mass MF based on DENIS and 2MASS discoveries of nearby ultracool dwarfs suggests a value of α in the range 1 to 2 (Reid et al. 1999). A deep survey for methane dwarfs suggests, however, that $\alpha \leq 0.8$ for disk brown dwarfs (Herbst et al. 1999).

Early searches for brown dwarfs in stellar clusters and associations (see eg. Rieke & Rieke 1990; Stauffer, Hamilton & Probst 1994; Jameson & Skillen 1989) and the subsequent confirmation of their existence (Rebolo, Zapatero Osorio, & Martín 1995; Basri, Marcy & Graham 1996; Rebolo et al. 1996) prompted among other questions the nature of the behavior of the MF in the brown dwarf domain and whether the fragmentation process can extend beyond the deuterium-burning mass limit. Several studies in very young clusters have provided partial answers to these questions (Bouvier et al. 1998; Luhman & Rieke 1999; Luhman et al. 1998, 2000; Barrado y Navascués et al. 2001a; Tamura et al. 1998; Lucas & Roche 2000; Hillenbrand & Carpenter 2000; Najita, Tiede & Carr 2000; Martín et al. 2000; Moreaux, Bouvier & Stauffer 2001). In spite of considerable progress made in recent years, the incompleteness of the photometric surveys at very low masses and the lack of a well defined spectroscopic sequence have prevented a reliable description of the MF over the whole brown dwarf regime. Here we present a determination of the MF for the σ Orionis young stellar cluster, which is reliable and complete down to the deuterium-burning mass limit, and a first estimate on how this MF extends to smaller masses, i.e., to the planetary regime.

2. Age, distance, and extinction in the σ Orionis cluster

The σ Orionis cluster belongs to the Orion OB1b association, for which an age of 1.7–7 Myr and a distance modulus of 7.8–8.3 are estimated based on studies carried out on massive stars (Blaauw 1964, 1991; Warren & Hesser 1978; Brown, de Geus & de Zeeuw 1994). The spectral type of the central star of the same name is O9.5 V. In order to account for the location of this star in the hydrogen-burning phase, its age must be younger than 5 Myr (on the basis of models with winds from Meynet et al. 1994). Recent investigations of the low-mass stellar and brown dwarf cluster populations have confirmed that σ Orionis has indeed a very young age in the interval 1–5 Myr (Béjar, Zapatero Osorio & Rebolo 1999 (BZOR); Wolk & Walter 2000), which is consistent with the estimates found for the massive stars. The inferred MF in σ Orionis may be very close to the true initial mass function (IMF) since no significant dynamical evolution is expected for cluster members. Additionally, the distance to the cluster is known through the determination

provided by *Hipparcos* of the distance modulus of $m - M = 7.7 \pm 0.7$ (value given for the central star). This measurement is in agreement with previous distance determinations of the OB1b subgroup. The σ Orionis star is affected by a low extinction of $E(B - V) = 0.05$ (Lee 1968), thus, the associated cluster is expected to exhibit very little reddening. From the comparison of the colors of some of the σ Orionis objects with counterparts of the same spectral type in the Pleiades and the field, BZOR did not find any significant reddening. In addition, the location of a larger sample of objects in the $I - J$ vs $J - K$ color-color diagram shows that their infrared excesss $E(I - J)$ is smaller than 0.3 mag (i.e., $A_V \leq 1$ mag, on the basis of the relationships given in Rieke & Lefobski 1985). All these properties of youth, proximity and low extinction confirm this cluster as a very interesting site for investigating the IMF.

3. Surveys and membership selection criterion

In order to construct the brown dwarf MF in the σ Orionis cluster we have combined optical (IZ) and near-infrared (J) surveys recently conducted around the central star (Zapatero Osorio et al. 2000; BZOR; Béjar 2000). New observations in the optical range were obtained with the Wide Field Camera instrument mounted on the primary focus of the 2.5–m Isaac Newton Telescope at the Roque de los Muchachos Observatory on 1998 November 12–13 (Béjar 2000). Images were bias-substracted and flat-fielded within the IRAF[1] environment. Instrumental magnitudes were transformed into observed magnitudes by differential photometry of objects in common with images taken under photometric conditions with the IAC80 telescope (Teide Observatory), which were calibrated in the Cousins system by observing Landolt's (1992) standard stars at different airmasses. Near infrared photometry in the J–band has been acquired using the 3.5–m telescope at the Calar Alto Observatory on 1998 October 27–31 (Zapatero Osorio et al. 2000). In addition, K–band photometry has been obtained on individual candidates with the 1.5–m Carlos Sánchez Telescope at Teide Observatory (1998 September 18, 2000 January 27, 2000 February 20), the 2.2–m telescope at Calar Alto Observatory (2000 February 16–18) and the 3.8–m United Kingdom Infrared telescope (UKIRT) at the Mauna Kea Observatory (2000 December 5–6). Raw frames were reduced following standard techniques in the infrared, which include sky-substraction and flat-fielding. The photometric calibration in the UKIRT system was achieved with faint standard stars (Hunt et al. 1998) observed at different airmasses on the same nights, except for the UKIRT data, which were calibrated later

[1]IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

using objects in comon with images taken under photometric conditions with the 1.23–m telescope at Calar Alto Observatory during 2000 January 22–23. The IZ and J-band data of these surveys overlap in a sky region of 847 arcmin^2 (the location of this region is shown in Fig.1 of BZOR). Therefore we restrict our MF analysis to this particular region of the cluster in which we have three color photometry for all candidate members, with limiting $I_{\rm Cousins}$ and $J_{\rm UKIRT}$ magnitudes of 23.8 and 21.2, and completeness magnitudes of 21.5 and 19.5, respectively. We have adopted as the limiting magnitude of our survey the detection of 95% of the total number of point-like sources on the frames; and as completeness magnitude the value at which the number distribution of detections as a function of magnitude deviates from an exponential law.

Spectroscopic observations of a total of 14 candidates in σ Orionis have confirmed them as cluster members (see BZOR, Béjar et al. 2000; Zapatero Osorio et al. 1999, 2000). We note that nine of them are located in the overlapping area of 847 arcmin^2. The 14 members give a well defined spectroscopic sequence from M6 (the most luminous and bluest targets) down to L4 (the reddest ones close to the limiting magnitude of the survey). Available I and J-band observations for these objects allow us to define the location of the low-mass star and brown dwarf sequence of the cluster (Figure 1), which we will adopt as a reference for the identification of cluster members. This location is suitably reproduced by the combination of the 5 Myr "dust-free and dusty" Lyon models (Baraffe et al. 1998; Chabrier et al. 2000) as shown in Figure 1. Below $I = 20$ we expect dust condensates in the atmosphere of cluster members cooler than M9, and so the dusty models seem to be more appropiate.

In the 847 arcmin^2 region under consideration we identify a total of 64 photometric candidates that are distributed along the theoretical and observational sequences with a dispersion around 0.5 mag. They seem to be very young objects and have colors redder than the 10 Myr isochrone given by the dust-free Lyon models (see Fig. 1). All the candidates have $I-Z$ colors and I magnitudes consistent with cluster membership. Follow-up K-band photometry for 17 of them also indicates their belonging to the I vs $I-K$ cluster sequence, which reinforces their very likely membership (BZOR; Béjar et al. 2000; Zapatero Osorio et al. 2000). In addition, we have very recently obtained spectra for 6 of our faintest candidates; based on our preliminary analysis these objects fit the expected spectroscopic sequence and so are bona fide low-mass members with a very high probability (Barrado y Navascués et al. 2001c). The photometric and spectroscopic data of our candidates and those members defining the cluster sequence are shown in Tables 1 and 2. In the latter we have not included the six candidates from Barrado y Navascués et al. (2001c). As explained in the previous section we do not find any evidence for reddening or infrared excesses and so we have not applied any extinction correction to our data. ¿From the

successful spectroscopic results along the photometric sequences we conclude that our selection criterion using optical and near-infrared photometry is very efficient in identifying true members of the cluster. A similar criterion for membership has proved successful in low-extinction clusters such as the Pleiades (Zapatero Osorio et al. 1997; Martín et al. 2000; Moreaux et al. 2001) and IC 2391 (Barrado y Navascués et al. 2001b).

4. The mass spectrum of brown dwarfs and planetary mass objects

The cluster luminosity function (LF) have been derived by counting the number of objects per magnitude interval in the I band, and it is shown in Figure 2. The first bin, M_I = 7.5–8.5, corresponds to stars so bright that were saturated in some of the images of the surveys under consideration. Fortunately, the BZOR data allowed us to make an estimate of the counts for this massive bin which was conveniently normalized to the present survey. We can see in Figure 2 that the LF is rising up to M_I=9 mag and then falls down and becomes flat from M_I=11.5 mag. The LF remains flat down to the completeness limit of our surveys. We note that the bins where the luminosity function shows a peak correspond to a mass range (0.08–0.05 $M_\odot$) which includes objects that have finished the deuterium burning phase (the more massive ones) and those actually burning deuterium. Both types of objects will have similar luminosities, if the age of the cluster is in the range 3–6 Myr, and therefore contribute to produce a peak in the LF.

In order to derive the IMF, we have first determined the masses for the σ Orionis members following a similar procedure to that described in Zapatero Osorio et al. (2000), which means that we adopted the mass–luminosity relationship given by the Lyon models (Baraffe et al. 1998; Chabrier et al. 2000). In favor of these models it can be argued that they have been successful in fitting the mass–luminosity relation in various optical and infrared passbands (Baraffe et al. 1998; Delfosse et al. 2001), as well as in predicting coeval ages for the members of several young multiple systems (White et al. 1999; Luhman 1999), and that they provide a good fit to the infrared photometric sequence in the Pleiades and σ Orionis clusters (Martín et al. 2000; Zapatero Osorio et al. 2000). Additionally, the Lyon tracks provide magnitudes and colors in the filters of interest as a function of mass, while in order to transform the effective temperatures and luminosities of other models into observables we would have to use bolometric corrections.

The σ Orionis cluster substellar IMF is illustrated in Figure 3, where the mass spectrum representation on a logarithmic scale is provided. For the age of 5 Myr a single power-law fit facilitates a reasonable representation of the data points with a slope of $\alpha = 0.8 \pm 0.4$ in the mass range which goes from very low mass stars ($0.2\,M_\odot$) through the whole

brown dwarf domain to $0.013\,M_\odot$. The uncertainty of ± 0.4 in the α index accounts for possible different ages of the cluster and the use of other evolutionary models. We have investigated the sensitivity of our mass spectrum to age by deriving α for ages from 3 Myr to 10 Myr. The values found were between 0.5 to 1.0. This interval also accounts for an uncertainty of 0.2 mag in the estimation of the cluster distance modulus. The dependence of the mass spectrum on theoretical models is even more uncertain. Our calculations considering Burrows et al. (1997) isochrones yield α values up to 0.4 higher depending on age. Our main result is that the very low-mass stellar and substellar mass spectrum of the σ Orionis cluster is generally rising toward lower masses. IMFs with slopes in the range 0.4–0.8 below the star–substellar mass borderline, have been obtained recently for other young clusters (Luhman et al. 2000; Lucas & Roche 2000; Hillenbrand & Carpenter 2000; Najita et al. 2000; Martín et al. 2000; Moreaux et al. 2001), showing that the formation of brown dwarfs is a quite common process in the Galactic disk.

A remarkable feature of Figure 3 is the evidence for an extension of the IMF into the domain of planetary masses (i.e lower than the deuterium burning mass). Despite the incompleteness of our survey and the possible contamination of several cluster non-members at these very low masses (see details in Zapatero Osorio et al. 2000), the planetary mass interval is rather well populated. This indicates that free-floating planetary mass objects with masses 0.013–0.005 $M_\odot$ are abundant in σ Orionis. We find no evidence for a "bottom end" of the IMF in the mass interval covered by our analysis, i.e., there is no obvious deficit of objects near and beyond the deuterium-burning mass limit. Deeper surveys will be needed to determine the existence and location of a minimum-mass limit in the IMF.

5. Conclusions and future perspectives

Recent searches have found a significant population of brown dwarfs in the σ Orionis cluster. We have estimated the mass spectrum, $dN/dm \propto M^{-\alpha}$, from very low mass stars ($0.2\,M_\odot$) to $0.013\,M_\odot$ and we have found that this is still rising across the whole brown dwarf regime with α=0.8 $\pm$ 0.4. Our results also suggest that the mass spectrum keeps rising down to $0.005\,M_\odot$. If the IMF in the σ Orionis cluster has α=0.8 down to 1 Jupiter mass, isolated planetary-mass objects in the mass range 1–12 $M_{\rm Jup}$ would be as numerous as brown dwarfs; and brown dwarfs and free-floating planets together would be as numerous as stars (see below for further details). However, their contribution to the total mass in the cluster would be less than 10 %.

The relatively large number of free-floating planetary-candidate members found in the σ Orionis cluster suggests that such low-mass objects form commonly in nature, and that

older and cooler isolated planets could be populating the Galactic disk and hence the solar neighborhood. Assuming that the IMF of σ Orionis is representative of the disk population, and extrapolating it to a mass of 1 $M_{\rm Jup}$, we obtain the densities of free-floating substellar systems given in Table 3. They are anchored to a density of stellar systems in the solar neighborhood of 0.057 pc^{-3} (Reid et al. 1999). With this estimate for an index of $\alpha \sim 1$ in the mass spectrum we would expect a total number of substellar objects around 435 within a radius of 10 pc, whereas there would be 239 stars. Isolated planets much older than objects in σ Orionis will be extremely faint and cool enough to show molecular features like the giant planets in the Solar System. Therefore, even if they form a large population in the solar neighborhood, their detection is a challenge to present-day observational capabilities. According to theoretical predictions of radiated fluxes at different wavelengths (Burrows et al. 1997; Allard et al. 1997), these objects in the mass range 1–12 $M_{\rm Jup}$ at the solar age could have effective temperatures of 100–300 K and an absolute magnitude of $M_{\rm J}$ = 20–25 and M_M=15–17. Current surveys such as 2MASS, DENIS, or SLOAN are unable to detect them out to distances greater than 1 parsec because they are too shallow. Deeper surveys, such as those reported by D'Antona, Oliva & Zeppirelli (1999) and Herbst et al. (1999) do not cover enough area. Free-floating planetary mass objects are extremely faint at optical and near-infrared wavelengths due to the absorption of methane and water, but they have a moderately transparent region around 5 μm. They could be identified with the *Space Infrared Facility* (*SIRTF*) out to distances of several parsecs from the Sun (Martín et al. 2001) or with wide ultra-deep ground-based near-infrared surveys such as the one planned with Megacam on the Canada-France-Hawaii telescope.

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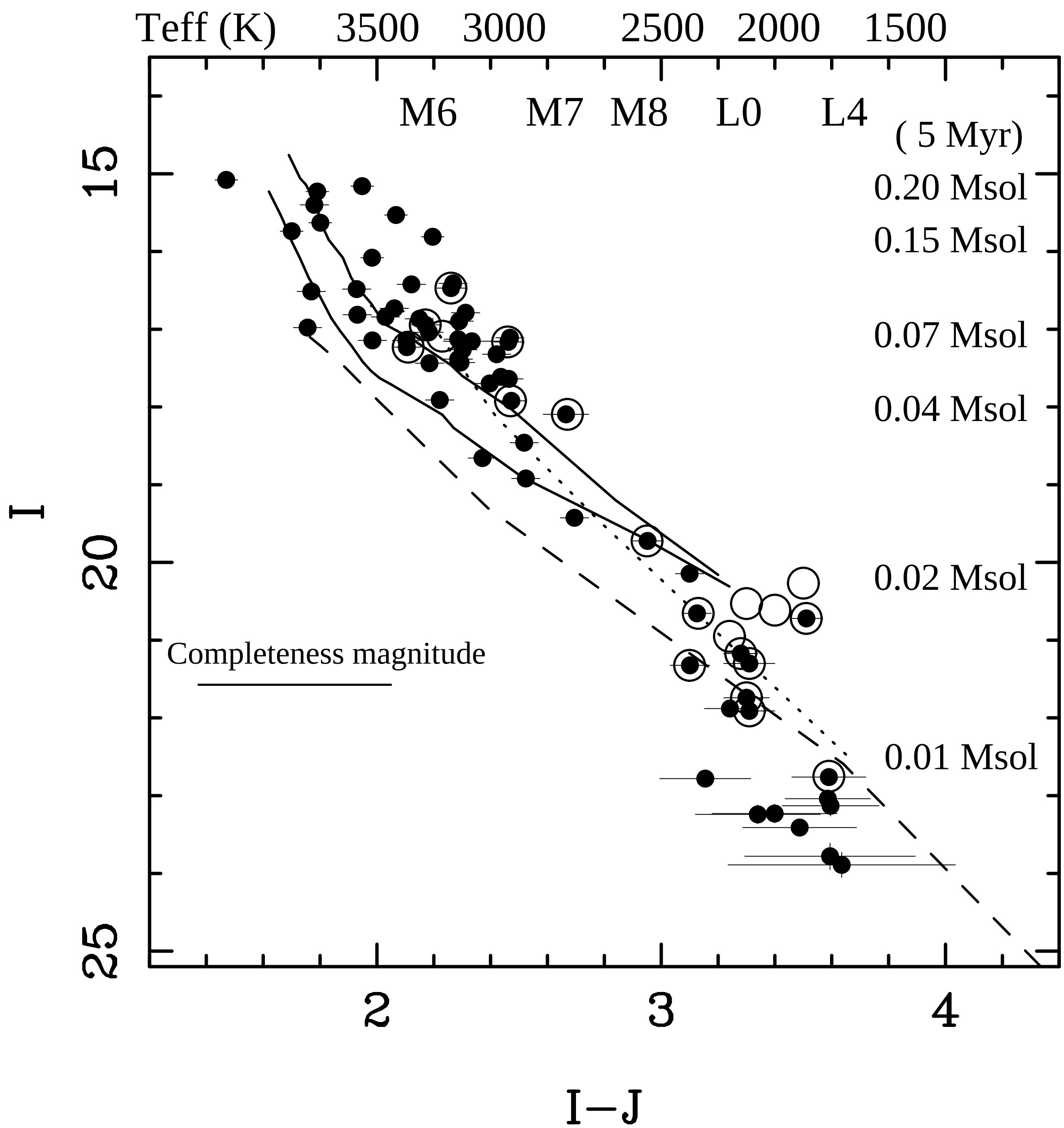
Fig. 1.— I vs. $I - J$ color–magnitude diagram for the σ Orionis cluster. Selected candidates are indicated with filled circles. The 5 Myr isochrones from the Lyon Group (Next Gen models—full line—and Dusty models—dashed line), and from the Arizona group (dotted line) and the 10Myr Next Gen isochrone (full line, bluer than 5Myr) are also shown for comparison. Open circles around filled symbols denote candidates with available spectroscopy confirming their membership. Empty open circles are for members with spectroscopy but located outside of the 847 arcmin^2, and thus not included in the MF computation. Error-bars are based on photometric uncertainties and are smaller than symbol size for the majority of the brightest objects. Completeness magnitude, spectral type, estimated temperatures and masses for the age of 5 Myr are also shown.

Fig. 2.— I-band luminosity function in the σ Orionis cluster. the dashed line indicates the completeness limit of our search. Error bars corresponding to Poissonian uncertainties are also shown.

Fig. 3.— The mass function of the σ Orionis cluster for substellar masses adopting several plausible ages. The best power-law fitting ($dN/dM \propto M^{-\alpha}$, dashed line) down to the brown dwarf-planet boundary ($\sim 0.013\ M_{\odot}$) gives $\alpha = 0.8 \pm 0.4$ for the most probable age of 5 Myr. Error bars correspond to Poissonian uncertainties (from the finite number of objects), except for the planetary-mass interval where the upper limit (arrow) denotes the incompleteness of the photometric and spectroscopic searches, and the lower error bar accounts for the possible contamination of cluster non-members as discussed in Zapatero Osorio et al. (2000).


Teff (K)
3500
3000
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I
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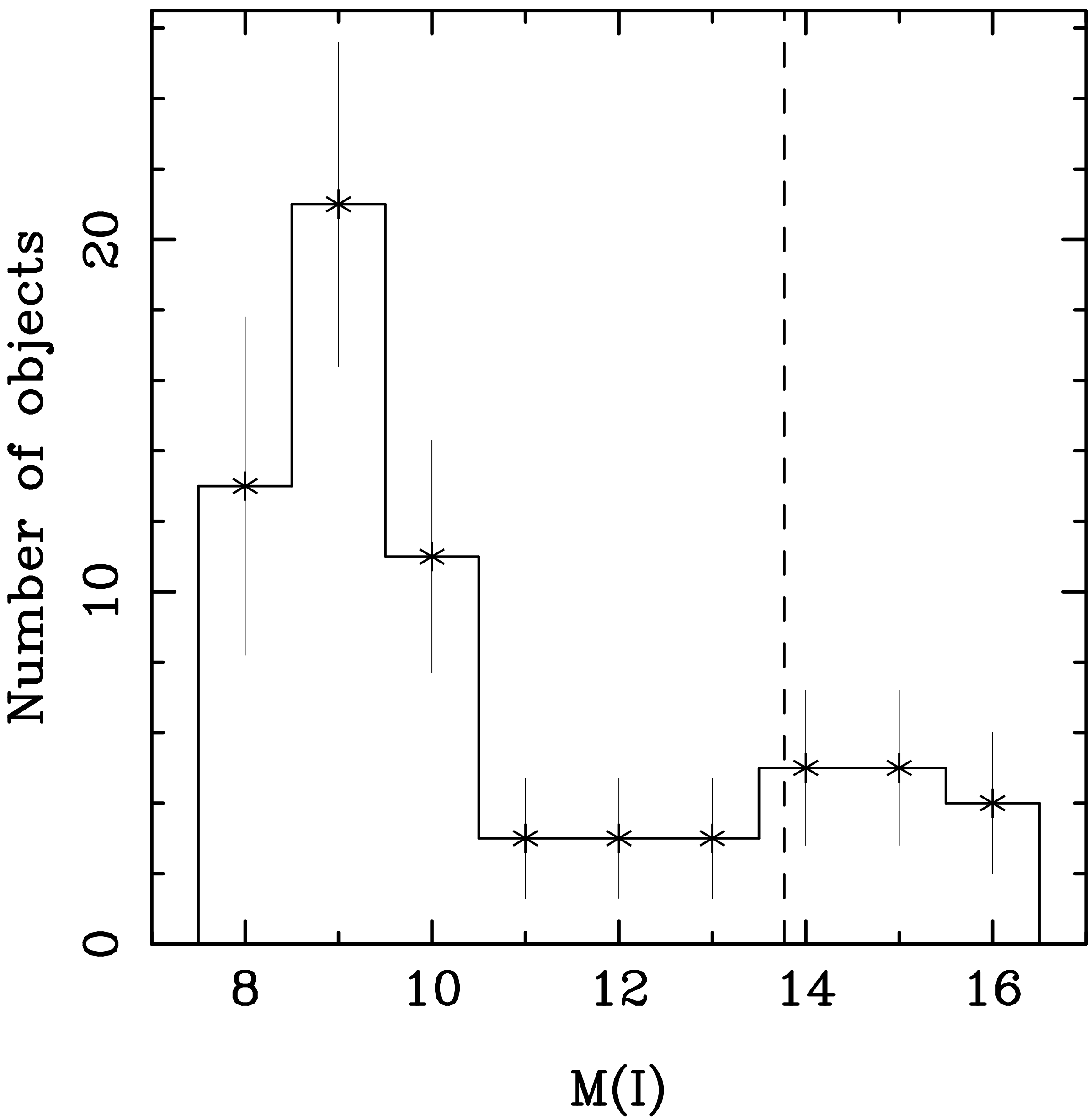
I−J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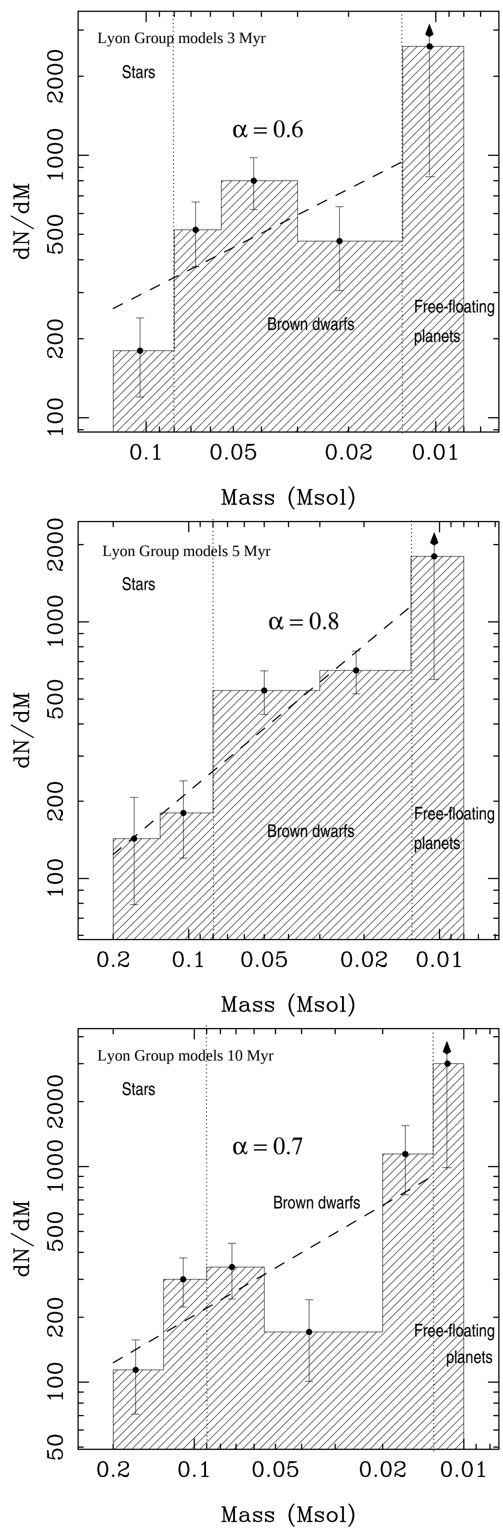
M(I)



Lyon Group models 3 Myr
Stars
α = 0.6
Brown dwarfs
Free-floating
planets
dN/dM
Mass (Msol)
Lyon Group models 5 Myr
Stars
α = 0.8
Brown dwarfs
Free-floating
planets
dN/dM
Mass (Msol)
Lyon Group models 10 Myr
Stars
α = 0.7
Brown dwarfs
Free-floating
planets
dN/dM
Mass (Msol)

Table 1. Photometric data of the selected candidates

Name (IAU)	prev. ID.	I	R-I	I-J	I-K	R.A.(J2000)	DEC.(J2000)
SOri J053911.7–022741	SOri1	15.08±0.04	1.70±0.07	1.47±0.04		05 39 11.7	–02 27 41
SOri J053920.8–023035	SOri3	15.16±0.04	2.15±0.07	1.95±0.04		05 39 20.8	–02 30 35
SOri J053939.2–023227	SOri4	15.23±0.04	2.16±0.07	1.79±0.04		05 39 39.2	–02 32 27
SOri J053920.1–023826	SOri5	15.40±0.05	1.86±0.07	1.78±0.05		05 39 20.1	–02 38 26
SOri J053847.5–023038	SOri6	15.53±0.04	2.00±0.07	2.07±0.04		05 38 47.5	–02 30 38
SOri J053908.1–023230	SOri7	15.63±0.04	2.07±0.07	1.80±0.04		05 39 08.1	–02 32 30
SOri J053907.9–022848	SOri8	15.74±0.04	1.87±0.07	1.70±0.04		05 39 07.9	–02 28 48
SOri J053817.1–022228	SOri9	15.81±0.04	2.06±0.07	2.20±0.04		05 38 17.1	–02 22 28
SOri J053944.4–022445	SOri10	16.08±0.04	1.97±0.07	1.98±0.04		05 39 44.4	–02 24 45
SOri J053944.3–023301	SOri11	16.424±0.008	1.94±0.06	2.12±0.05		05 39 44.3	–02 33 01
SOri J053757.4–023845	SOri12	16.471±0.010	1.75±0.05	2.26±0.05		05 37 57.4	–02 38 45
SOri J053813.1–022410	SOri13	16.410±0.018	1.93±0.06	2.27±0.05		05 38 13.1	–02 24 10
SOri J053909.9–022814		16.485±0.012		1.93±0.05		05 39 09.9	–02 28 14
SOri J053746.6–024328		16.514±0.003		1.77±0.05		05 37 46.6	–02 43 28
SOri J053911.4–023333		16.731±0.011		2.06±0.05		05 39 11.4	–02 33 33
SOri J053848.0–022854	SOri15	16.789±0.014	1.81±0.07	2.31±0.05	3.31±0.06	05 38 48.0	–02 28 54
SOri J053849.2–022358		16.813±0.017		1.93±0.05		05 38 49.2	–02 23 58
SOri J053915.0–024048	SOri16	16.843±0.008	1.91±0.06	2.03±0.05		05 39 15.0	–02 40 48
SOri J053721.0–022543	SOri19	16.867±0.008	2.06±0.06	2.15±0.05		05 37 21.0	–02 25 43
SOri J053825.6–023122	SOri18	16.896±0.014	2.02±0.07	2.29±0.05		05 38 25.6	–02 31 22
SOri J053904.4–023835	SOri17	16.945±0.009	1.88±0.06	2.17±0.05		05 39 04.4	–02 38 35
SOri J053923.3–024657	SOri28	16.979±0.008	2.29±0.08	1.76±0.05		05 39 23.3	–02 46 57
SOri J053829.0–024847		17.040±0.010		2.18±0.05	3.09 ±0.03	05 38 29.0	–02 48 47
SOri J053835.2–022524	SOri22	17.109±0.008	2.11±0.07	2.47±0.05		05 38 35.2	–02 25 24
SOri J053751.0–022610	SOri23	17.128±0.009	2.10±0.06	2.29±0.05		05 37 51.0	–02 26 10
SOri J053755.6–022434	SOri24	17.144±0.009	2.01±0.06	2.10±0.05		05 37 55.6	–02 24 34
SOri J053943.7–024729	SOri32	17.144±0.007	2.26±0.07	1.98±0.05		05 39 43.7	–02 47 29
SOri J053934.2–023847	SOri21	17.154±0.007	1.91±0.08	2.33±0.10		05 39 34.2	–02 38 47
SOri J053908.8–023958	SOri25	17.163±0.008	2.17±0.10	2.46±0.05		05 39 08.8	–02 39 58
SOri J053829.5–022517	SOri29	17.230±0.008	1.98±0.07	2.11±0.05		05 38 29.5	–02 25 17
SOri J053916.6–023827	SOri26	17.264±0.008	1.83±0.08	2.30±0.05		05 39 16.6	–02 38 27
SOri J053907.4–022908	SOri20	17.321±0.009	1.68±0.07	2.42±0.05		05 39 07.4	–02 29 08
SOri J053657.9–023522	SOri33	17.385±0.008	2.28±0.06	2.29±0.05		05 36 57.9	–02 35 22
SOri J053820.9–024613	SOri31	17.429±0.008	2.03±0.05	2.29±0.05		05 38 20.9	–02 46 13
SOri J053913.0–023751	SOri30	17.438±0.008	1.71±0.08	2.19±0.05		05 39 13.0	–02 37 51
SOri J053755.5–023308	SOri35	17.612±0.008	2.25±0.06	2.44±0.05		05 37 55.5	–02 33 08
SOri J053915.1–022152	SOri38	17.640±0.008	2.19±0.09	2.46±0.05		05 39 15.1	–02 21 52
SOri J053821.3–023336		17.697±0.013		2.40±0.05		05 38 21.3	–02 33 36
SOri J053926.8–023656	SOri36	17.911±0.008	1.94±0.14	2.22±0.05		05 39 26.8	–02 36 56
SOri J053832.4–022958	SOri39	17.922±0.008	2.24±0.10	2.47±0.05	3.18±0.07	05 38 32.4	–02 29 58
SOri J053736.4–024157	SOri40	18.095±0.009	2.18±0.05	2.67±0.08		05 37 36.4	–02 41 57
SOri J053936.4–023626		18.459±0.017		2.52±0.05		05 39 36.4	–02 36 26
SOri J053926.8–022614		18.657±0.008		2.37±0.05		05 39 26.8	–02 26 14
SOri J053948.1–022914		18.921±0.009		2.52±0.05		05 39 48.1	–02 29 14
SOri J053912.8–022453		19.425±0.008		2.69±0.05	4.09 ±0.10	05 39 12.8	–02 24 53
SOri J053825.6–024836	SOri45	19.724±0.009	2.75±0.017	2.95±0.05	4.07 ±0.09	05 38 25.6	–02 48 36
SOri J053946.5–022423		20.144±0.010		3.10±0.05	4.21 ±0.16	05 39 46.5	–02 24 23
SOri J053910.8–023715	SOri50	20.656±0.015		3.13±0.05	4.48 ±0.05	05 39 10.8	–02 37 15
SOri J053903.2–023020	SOri51	20.72 ±0.014		3.51±0.05	4.58 ±0.10	05 39 03.2	–02 30 20
SOri J053825.1–024802	SOri53	21.172±0.023		3.28±0.06	4.72 ±0.09	05 38 25.1	–02 48 02
SOri J053833.3–022100	SOri54	21.30 ±0.05		3.31±0.09	4.35 ±0.10	05 38 33.3	–02 21 00
SOri J053725.9–023432	SOri55	21.32 ±0.03		3.10±0.07	4.32 ±0.10	05 37 25.9	–02 34 32

Table 1—Continued

Name (IAU)	prev. ID.	I	R-I	I-J	I-K	R.A.(J2000)	DEC.(J2000)
SOri J053900.9-022142	SOri56	21.74 ±0.03		3.30±0.08	4.65 ±0.10	05 39 00.9	–02 21 42
SOri J053947.0-022525	SOri57	21.88 ±0.03		3.24±0.09		05 39 47.0	–02 25 25
SOri J053903.6-022536	SOri58	21.91 ±0.03		3.31±0.09	5.03 ±0.20	05 39 03.6	–02 25 36
SOri J053937.5-023042	SOri60	22.76 ±0.05		3.59±0.13	5.07 ±0.10	05 39 37.5	–02 30 42
SOri J053852.6-022846	SOri61	22.78 ±0.05		3.16±0.16		05 38 52.6	–02 30 46
SOri J053942.1-023031	SOri62	23.04 ±0.07		3.59±0.15	5.36 ±0.15	05 39 42.1	–02 30 31
SOri J053653.3-022414	SOri64	23.13 ±0.13		3.60±0.17	4.51 ±0.25	05 36 53.3	–02 24 14
SOri J053724.7-023152	SOri66	23.23 ±0.12		3.40±0.22		05 37 24.7	–02 31 52
SOri J053826.1-022305	SOri65	23.24 ±0.12		3.34±0.22	4.41 ±0.30	05 38 26.1	–02 23 05
SOri J053812.6-022138	SOri67	23.41 ±0.090		3.49±0.20		05 38 12.6	–02 21 38
SOri J053839.1-022805	SOri68	23.78 ±0.17		3.6 ±0.3		05 38 39.1	–02 28 05
SOri J053918.1-022855	SOri69	23.89 ±0.16		3.6 ±0.4		05 39 18.1	–02 28 55

Note. — Units of right ascension (J2000) are hours, minutes, and seconds, and units of declination (J2000) are degrees, arcminutes, and arcseconds. Coordinates are accurate to $\pm 1''$. All the available R-band photometry and I-band data for candidates SOri1–10 have been taken from BZOR. Photometric measurements for candidates SOri50-69 have also been presented in Zapatero Osorio et al. 2000.

Table 2. Spectroscopic data of σ Orionis members

Name	I	I-J	I-K	Spectral Type (PC3)	Spectral Type
SOri12*	16.471±0.010	2.26 ±0.05		M4.5	M6
SOri17*	16.945±0.009	2.17 ±0.05		M4.6	M6
SOri29*	17.230±0.008	2.11 ±0.05		M4.8	M6
SOri25*	17.163±0.008	2.46 ±0.05		M5.1	M6.5
SOri39*	17.922±0.008	2.47 ±0.08	3.18±0.07	M5.1	M6.5
SOri27	17.090±0.04	2.23 ±0.05	3.18±0.05	M5.1	M7
SOri40*	18.095±0.009	2.67 ±0.06		M5.6	M7
SOri45*	19.724±0.009	2.95 ±0.05	4.07±0.09	M8.0	M8.5
SOriJ053710.0-024302	20.266±0.011	3.5 ±0.3	4.9 ±0.4	M8.2	M8.5
SOriJ053636.3-024626	20.614±0.019	3.4 ±0.11		M9.4	M9.5
SOri47	20.530±0.05	3.30 ±0.10	4.79±0.15	L1.4	L1.5
SOri52	20.958±0.016	3.24 ±0.15	5.53±0.15	L0.5	L0.5
SOri56*	21.740±0.03	3.30 ±0.08	4.65 ±0.10	L0.5	L0.5
SOri60*	22.76 ±0.05	3.59 ±0.13	5.07 ±0.10		L4

Note. — Spectral type have been derived using pseudocontinuous index PC3 ([823.0–827.0]/[754.0–758.0], Martín et al. 1999) and from comparison with standard M dwarfs.

* Candidates within the 847 arcmin^2 of present survey.

Table 3. Substellar density in the solar vicinity

α	$\rho_{\rm BD}$ systems/pc^3	$N_{\rm BD}$ $d < 10$ pc	$\rho_{\rm Pl}$ systems/pc^3	$N_{\rm Pl}$ $d < 10$ pc	$N_{\rm tot}$ $d < 10$ pc
0.5	0.015	63	0.008	34	95
0.8	0.028	117	0.027	113	230
1.0	0.042	176	0.062	259	435
1.5	0.114	478	0.510	2136	2614

Note. — α indicates the exponent of the mass spectrum ($dN/dm \propto m^{-\alpha}$) and BD and Pl indicates brown dwarfs (0.075–0.013 $M_{\odot}$) and planetary mass objects (0.013–0.001 $M_{\odot}$), respectively